Naval Research Laboratory

Washington, DC 20375-5000

An Empirical Prediction Algorithm for Low-Frequency Acoustic Surface Scattering Strengths

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April 28, 1992

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

| 1. AGENCY USE ONLY (Leave blank) | 2. REPORT DATE
April 28, 1992 | 3. REPORT TYPE AND DATES COVERED
Interim |

4. TITLE AND SUBTITLE

An Empirical Prediction Algorithm for Low-Frequency Acoustic Scattering Strengths

5. FUNDING NUMBERS

PE - 62435N
PR - RJ35B01

6. AUTHOR(S)

Peter M. Ogden and Fred T. Erskine

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
Washington, DC 20375-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/FR/5160—92-9377

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Technology
Arlington, VA 22217

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

We propose an algorithm for calculating surface backscattering strength for grazing angles between 0° and 40°, for wind speeds between 0 and 40 knots and for frequencies between 50 and 1000 Hz. The algorithm is based on broadband SUS data collected during the Critical Sea Test series of at-sea experiments. It is intended as a replacement for the Chapman-Harris empirical formula presently used in virtually all low-frequency acoustic reverberation models. The algorithm represents an interim step between the original Chapman-Harris formula and a more detailed description of surface scattering that will take into account a wider variety of environmental factors.

14. SUBJECT TERMS

Reverberation
Scattering strength
Active sonar
Sea surface scattering
Underwater acoustics

15. NUMBER OF PAGES
19

16. PRICE CODE

| 17. SECURITY CLASSIFICATION OF REPORT
UNCLASSIFIED | 18. SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED | 19. SECURITY CLASSIFICATION OF ABSTRACT
UNCLASSIFIED | 20. LIMITATION OF ABSTRACT
SAR |

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AN EMPIRICAL PREDICTION ALGORITHM FOR LOW-FREQUENCY ACOUSTIC SURFACE SCATTERING STRENGTHS

1. INTRODUCTION

Acoustic models that attempt to predict reverberation levels for a particular set of environmental and acoustic parameters require a model for the level of surface backscatter. For most low-frequency (i.e., below 1 kHz) models, as well as for general sonar equation calculations, the surface backscatter component of the general reverberation field is modeled using the empirically-derived Chapman-Harris formula (Chapman and Harris 1962). This formula is

$$SS = 3.3\beta \log(\theta/30) - 42.4 \log \beta + 2.6,$$

where

$$\beta = 158(U f^{1/3})^{-0.58},$$

and SS is the surface scattering strength in dB,[*] θ is the grazing angle in degrees, U is the wind speed in knots, and f is the acoustic frequency in Hz. This relationship was derived from data collected in deep water off the coast of Bermuda by using signal, underwater sound (SUS) explosive charges as sources and a single receiving hydrophone. The data were collected during a single 52-h period when surface conditions ranged from sea state 0 to sea state 6, and wind speeds ranged from 0 to 30 knots. The data were measured in octave frequency bands from 400 to 6400 Hz. Later work by Chapman and Scott (1964) extended the data range to lower frequencies.

While the Chapman-Harris empirical formula adequately describes the levels of surface scattering for some combinations of frequency and surface conditions, recent work in programs such as the Critical Sea Test[†] (CST) shows that there are other frequency/environment regimes in which the Chapman-Harris predictions are not adequate. Here we propose a generalization of the Chapman-Harris formula for modeling surface scattering strength as a function only of frequency, wind speed, and grazing angle, based on new observations of surface scattering made during five CST at-sea exercises. The data on which this generalization are based will not be presented here, as they have been reported elsewhere (Ogden 1992; Erskine et al. 1992). Rather, this report summarizes the results obtained in the CST exercises and discusses the algorithm based on those results.

This algorithm is intended to be an initial step between the existing Chapman-Harris formula and a more detailed description of surface scattering that is the subject of continuing research. The algorithm provides a better estimate of scattering strength in the 50 to 1000 Hz band for the grazing angles and wind speeds covered in this report than does Chapman-Harris. However, additional

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Manuscript approved February 23, 1992.

[*] SS is a dimensionless quantity, using the definition of $SS = 10 \log \frac{I_{scat}}{I_{inc}}$ given by Urick (1983).

[†] Sponsored by Space and Naval Warfare Systems Command, PMW-183.

work is needed on the surface scattering problem to arrive at a more detailed understanding of the dependence of surface reverberation on environmental and acoustic parameters.

There are several qualifications that must be applied to the result proposed in this report. The most important qualification is that it has been recognized from CST and other work on surface scattering that a prediction of scattering strength based on a single environmental parameter (i.e., on instantaneous wind speed alone) is not adequate. For example, it has been found that a parameter like sea state that contains some wind history appears to be a better predictor of surface scattering strength than wind speed (Ogden 1992; Erskine et al. 1992). For this reason, it would be preferable to use sea state as a parameter rather than wind speed in models of surface reverberation. However, to make the algorithm proposed in this report as compatible as possible with existing models, the dependence of scattering strength on wind speed alone has been retained. A second qualification is that there has been no attempt made in the development of the proposed algorithm to do any detailed functional fitting of the CST surface scatter data. The approach we have taken is to identify empirical regimes in the range of frequency/surface conditions where existing theoretical or empirical formulas seem to be appropriate and to merge them smoothly into a single predictive algorithm.

2. DESCRIPTION OF CST DATA

One experiment that has been a component of each CST at-sea exercise has been the measurement of surface backscattering strengths using SUS charges as sources and a towed horizontal line array as a receiver. In this experiment, the SUS charges are detonated directly beneath the receiver, and the backscattered surface returns are received on a set of hydrophones. The signals from these hydrophones are then beamformed and Fourier analyzed into narrowband (generally 4 Hz) reverberation levels. Scattering strengths are then calculated from these reverberation levels by combining them with the source level for the SUS charge, the computed transmission loss from the source to the surface and from the surface to the receiver, and the area insonified by the signal during a particular period of time. Because SUSs are broadband sources, scattering strengths may be measured simultaneously for a wide range of frequencies. In the CST program, the SUS measurements are generally analyzed over a range of frequencies from $\sim$70 Hz to about 1 kHz. The grazing angles covered by this experiment are usually between about 30° and around 5° to 7°. The lower limit is generally determined by the time of the arrival of the bottom fathometer return. A detailed description of the acquisition and analysis process may be found elsewhere (Ogden and Erskine 1989).

During the first four CST at-sea exercises, a total of 31 SUS surface scatter data sets were collected. Each data set took roughly an hour and involved the deployment of 10 to 20 SUS charges. These measurements were carried out under a range of environmental conditions; during the various SUS tests, wind speeds varied from 6 to 28 knots (corrected to a height of 19.5 m[*]), with sea states from 1 to 4.5.

---

[*]An often-used reference height that comes from the wave spectra data collected by Moskowitz (1964) and analyzed by Pierson and Moskowitz (1964).

Each of the individual runs was analyzed to give scattering strength as a function of grazing angle, frequency, and environmental conditions. The results of these runs were then compared to empirical and theoretical predictions of scattering strengths for the conditions that occurred during the runs. Figure 1 gives the results of these comparisons and summarizes many of the SUS runs by dividing the appropriate frequency and wind speed space into three regimes. (It is worth noting again that the use of wind speed as an environmental descriptor here is not an optimum choice; it does not include the other effects, such as wind history, that are known to be important in the prediction of scattering strengths.)

In the regime that encompasses the lowest wind speeds at all frequencies and increasingly higher wind speeds at lower frequencies, the scattering strength results were found to be in reasonable agreement with the predictions of air-sea interface scattering as described by perturbation theory (see, for example, Thorsos 1990). The principal predictions of perturbation theory for the range of frequencies, grazing angles, and wind speeds relevant here are that the scattering strengths should have a $\tan^4 \theta$ dependence on grazing angle and relatively little dependence on frequency and wind speed.

At higher wind speeds and higher frequencies, the SUS results were found to be in reasonable agreement with the Chapman-Harris empirical formula given previously. While the grazing angle dependence of Chapman-Harris is roughly similar to that of perturbation theory, the Chapman-Harris formula has considerably more wind speed and frequency dependence than perturbation theory predictions. This enhanced dependence results in scattering strength levels that are considerably higher than can be expected from scattering from the air-water interface, which strongly suggests that the principal scattering mechanism must be different from just the scattering off a rough surface. It is widely believed that subsurface bubble clouds and/or plumes give rise to this enhanced acoustic scattering.

In between these two regions is a transitional region where the two mechanisms are (presumably) competing as the dominant source of scattering. The scattering strengths in this regime are generally somewhere between the predictions of perturbation theory and Chapman-Harris, but the exact levels are found to depend on environmental and acoustic parameters in a manner that is not yet well understood.

As previously mentioned, the regimes shown in Fig. 1 were determined by examining many individual scattering strength vs grazing angle curves and making a judgment as to whether they were best described by Chapman-Harris or perturbation theory, or were in-between these descriptions. The boundaries of the three regimes were determined through the production of the plot shown in Fig. 2. In this plot, each point represents a grazing angle vs scattering strength curve at a single frequency, with the letter indicating the best description of the entire curve. (Note that in some parts of the frequency/wind speed regime, Chapman-Harris and perturbation theory give similar predictions. These points were normally assigned to perturbation theory.) After plotting all the points, the boundaries of the regimes were determined visually rather than by using an analytical scheme.
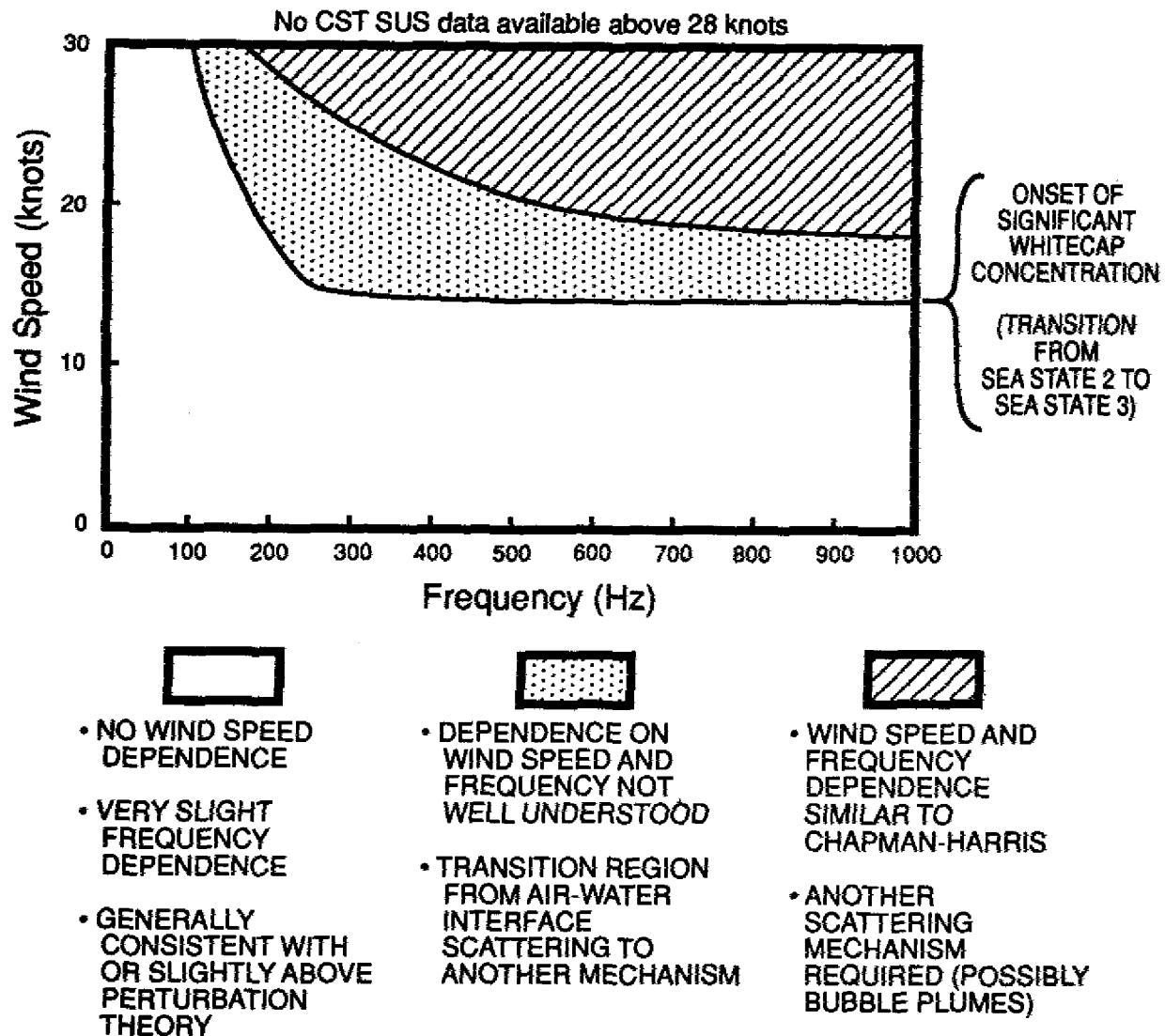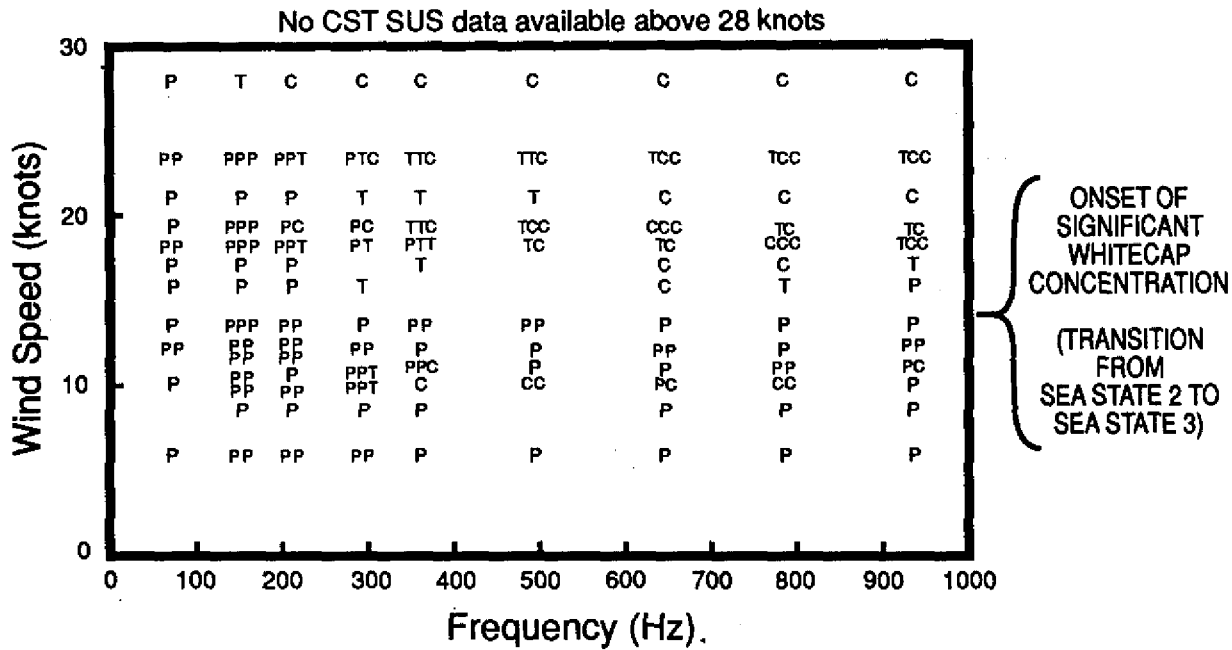
No CST SUS data available above 28 knots

Fig. 1 — Surface scatter results from the CST SUS tests

No CST SUS data available above 28 knots

Fig. 2 – Individual points used to produce Fig. 1

P: Results are in rough agreement with
   perturbation theory

T: Results are in a transition region
   from perturbation theory to
   Chapman-Harris levels

C: Results are in general agreement with
   the levels given by the Chapman-Harris
   empirical formula

3.   SCATTERING STRENGTH ALGORITHM

The surface scattering algorithm presented in this report is a two-step procedure. First, the wind speed and frequency are used to decide which of the regimes shown in Fig. 1 is appropriate. Second, the scattering strength is calculated from the wind speed, frequency, and grazing angle by using one of three methods that correspond to the three regimes. The three calculations of scattering strength used in this algorithm are (1) first-order perturbation theory, (2) the Chapman-Harris empirical formulation, and (3) an interpolation between (1) and (2).

The first step in translating the regime plot in Fig. 1 into an algorithm was to put the boundaries of the regions into analytical form. The lower boundary, between the perturbation theory region and the transition region, was approximated by two line segments. The upper boundary, between the transition region and the Chapman-Harris region, was fit by a cubic polynomial. These two boundary curves intersected at about 35 knots and 50 Hz, so 50 Hz was taken as the low-frequency cutoff to the algorithm. We have analyzed data up to ~ 1 kHz, so this was used as the upper frequency cutoff. As noted previously, the range of grazing angles over which we have data is about $5°$ to $30°$, but we have extended the upper and lower limits of the algorithm to $1°$ and $40°$ respectively, as these limited extrapolations are probably valid. (Perturbation theory becomes a poor approximation at high grazing angles unless other effects are added, thus we have used a $40°$ cutoff.) An arbitrary upper limit of 40 knots was included, while a lower wind speed limit of 5 knots was included for reasons that will be discussed later.

For lower-wind, lower-frequency cases, the algorithm uses two-dimensional first-order perturbation theory for calculating scattering strengths. A presentation of the relevant equations is given by Thorsos (1990). Using the notation of Thorsos, the 2-D backscattering cross section $\sigma_{2D}^{(2)}$ is

$$\sigma_{2D}^{(2)} = 4k_{iz}^4 W(2\bar{K}_{ix}),$$

where k_{iz} is the incident acoustic wavenumber in the z direction, $W(\bar{K})$ is the 2-D roughness spectral density, $\bar{K}$ is the "transverse" surface wave vector $(\bar{K} = K_x \hat{x} + K_y \hat{y})$, and the scattering strength is given by $10 \log \sigma_{2D}^{(2)}$, where the superscript on σ refers to the nature of the terms included in a first-order perturbation calculation. If we make the assumption that the wind direction is along the x axis, and we use the definition of $W(\bar{K})$ given by Thorsos, the expression for σ becomes

$$\sigma_{2D}^{(2)} = 4k_{iz}^4 \frac{S(2k_{ix})}{k_{ix}} \cdot \Phi,$$

where Φ is the azimuthal dependence of the wave spectrum, and we have chosen to take $S(2k_{ix})$ as the Pierson-Moskowitz 1-D wave spectral density (Pierson and Moskowitz 1964) given by

$$S(2k_{ix}) = \frac{\alpha}{32 |k_{ix}|^3} \exp\left[-\beta \left(\frac{g}{2 |k_{ix}| U^2}\right)^2\right],$$

where $\alpha = 8.10 \times 10^{-3}$, $\beta = 0.74$, $g = 9.81$ m/s^2, and U is the wind speed in m/s at a height of 19.5 m. Since the input to the algorithm is the acoustic frequency f, we use the definitions

$k_{iz} = \frac{2\pi f}{c}\sin\theta$ and $k_{ix} = \frac{2\pi f}{c}\cos\theta$ in the above expression to get

$$\sigma_{2D}^{(2)} = 1.01 \times 10^{-3}\tan^4\theta\exp\left[-\frac{1.01\times 10^6}{f^2 U^4\cos^2\theta}\right]\cdot\Phi.$$

For the surface scatter algorithm we have assumed that surface roughness is isotropic, in which case $\Phi = \frac{1}{2\pi}$, and we finally arrive at

$$\sigma_{2D}^{(2)} = 1.61 \times 10^{-4}\tan^4\theta\exp\left[-\frac{1.01\times 10^6}{f^2 U^4\cos^2\theta}\right].$$

As noted previously, $10\log\sigma_{2D}^{(2)}$ is the perturbation theory expression contained in the surface scatter algorithm.

The only additional modification to the actual calculation is that the wind speed lower limit is set to 5 knots, with values lower than this rounded to 5 knots. Since the Pierson-Moskowitz formula was determined by measuring surface wave spectra for wind speeds between 20 and 40 knots, it is not at all clear that it is applicable to very low wind speeds. Since there is evidence that surface scattering strengths are still reasonably well-characterized by perturbation theory for wind speeds around 4 to 5 knots (Ogden and Erskine, to be published), we have chosen to put a lower limit on the wind speed to avoid the return of unreasonable values at low frequencies. As with the grazing angle cutoffs, the low wind speed cutoff is unlikely to affect any serious reverberation calculations, since surface scatter from wind speeds below 5 knots is unlikely to be of much importance compared to other noise sources.

The remainder of the algorithm is straightforward to describe. At higher frequencies and higher wind speeds, the Chapman-Harris empirical formula presented earlier is used. In the transition region, both the perturbation theory scattering strength SS_{pert} and the Chapman-Harris scattering strength SS_{CH} are calculated. Then a simple interpolation on the resulting dB values is performed:

$$SS_{total} = \alpha SS_{CH} + (1-\alpha)SS_{pert},$$

where

$$\alpha(f_{input}) = \frac{\text{input wind speed} - \text{wind speed at pert. theory boundary}}{\text{wind speed at CH boundary} - \text{wind speed at pert. theory boundary}},$$

where the boundary wind speeds are evaluated at the input frequency. Thus at a particular frequency, a wind speed close to the perturbation theory regime boundary will give a scattering strength close to the perturbation theory level, while a wind speed just below the Chapman-Harris boundary will result in a scattering strength that is close to Chapman-Harris. While this approach is clearly an approximation, it does reflect the observed fact that for conditions in the transition region, the scattering strength values are usually somewhere between the two extremes.

To test the algorithm, we generated a series of plots that hold one of the three input parameters (frequency, grazing angle, wind speed) constant and show how scattering strength varies as a function of the other two. Examples of these plots are shown in Figs. 3 through 8. In Figs. 3 and
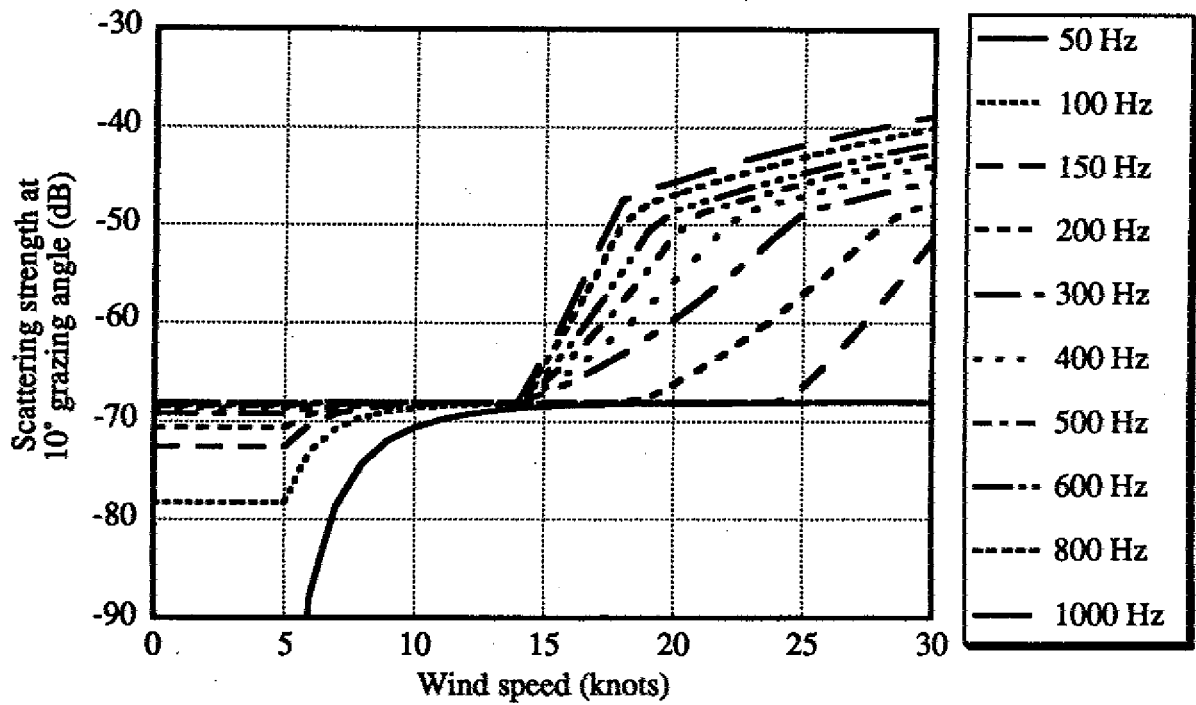
Fig. 3 – Surface scattering strengths as a function of wind speed and frequency for a grazing angle of 10°
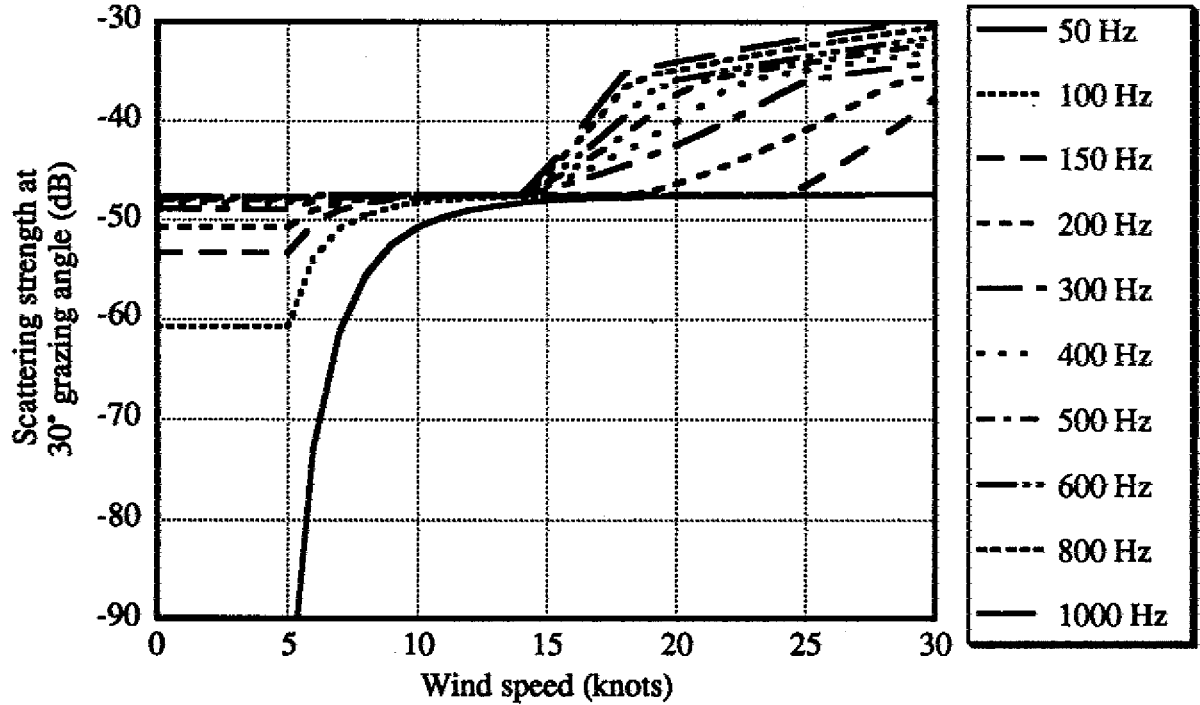

Fig. 4 – Surface scattering strengths as a function of wind speed and frequency for a grazing angle of 30°
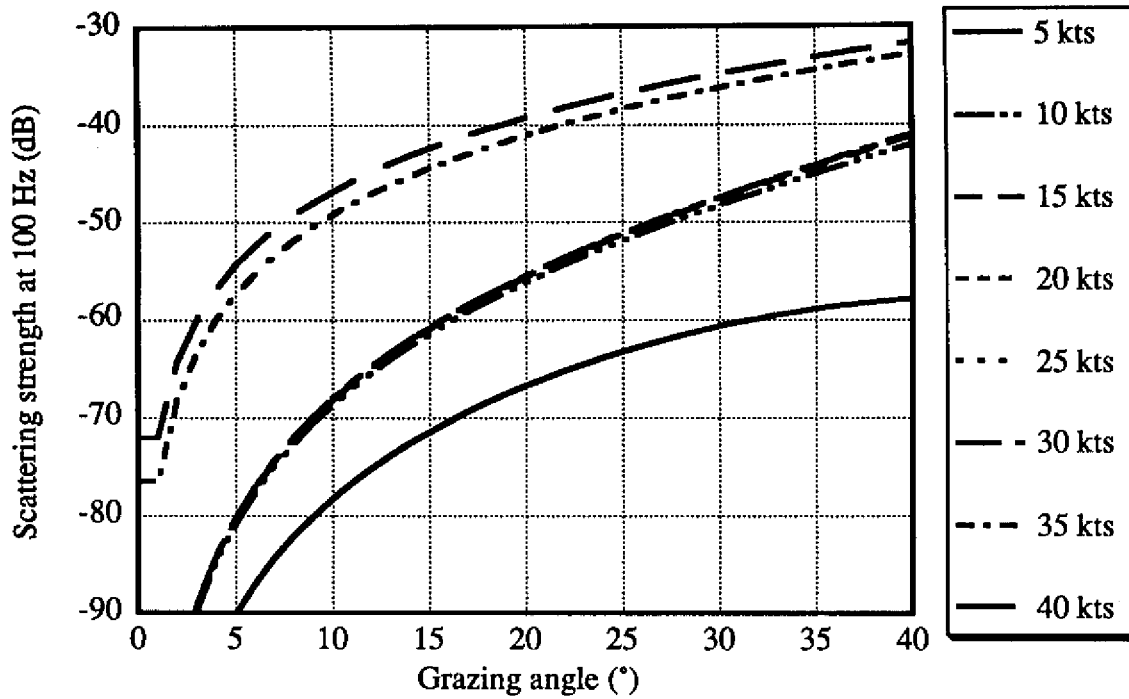
Fig. 5 – Surface scattering strengths as a function of grazing angle and wind speed for a frequency of 100 Hz
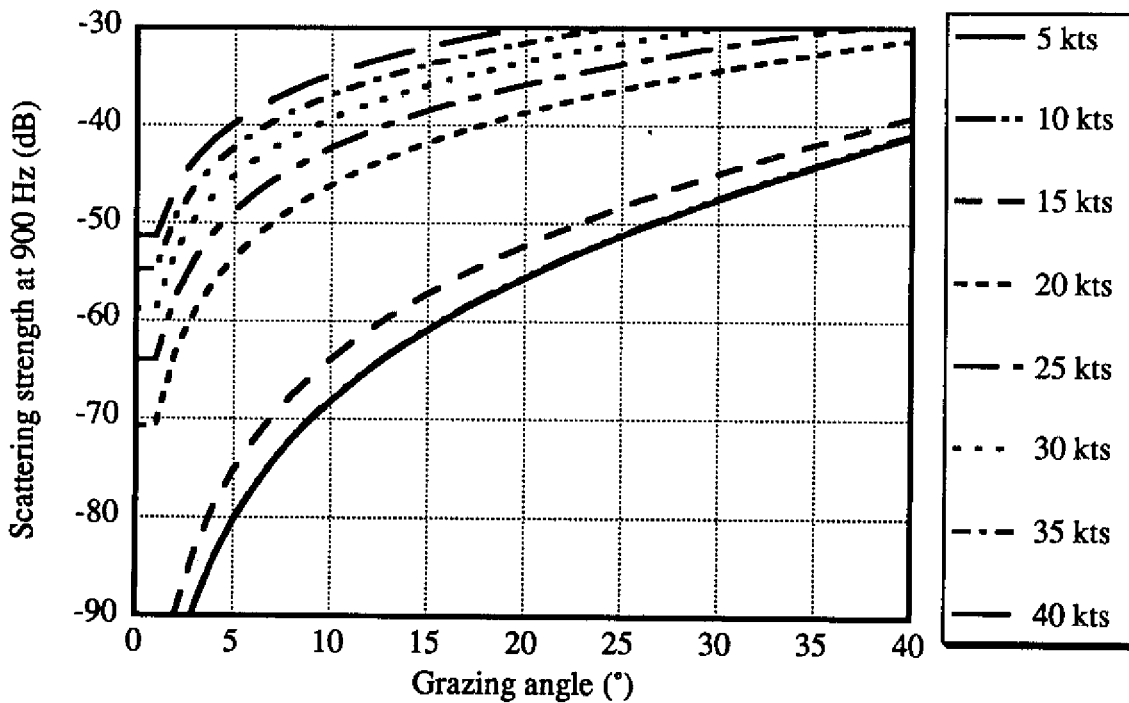

Fig. 6 – Surface scattering strengths as a function of grazing angle and wind speed for a frequency of 900 Hz

Scattering strength at 5 knots (dB)

Grazing angle (°)

50 Hz
100 Hz
150 Hz
200 Hz
300 Hz
400 Hz
500 Hz
600 Hz
800 Hz
1000 Hz
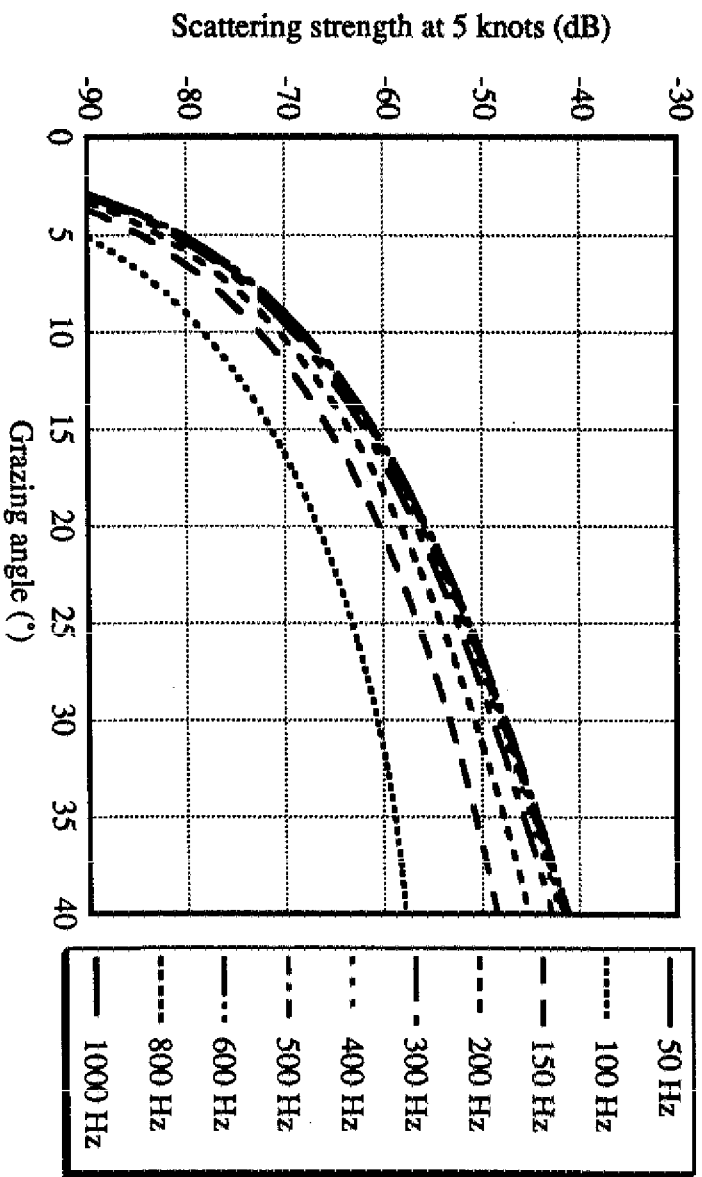
Fig. 7 — Surface scattering strengths as a function of grazing angle and frequency for a wind speed of 5 knots

Scattering strength at 30 knots (dB)

Grazing angle (°)

50 Hz
100 Hz
150 Hz
200 Hz
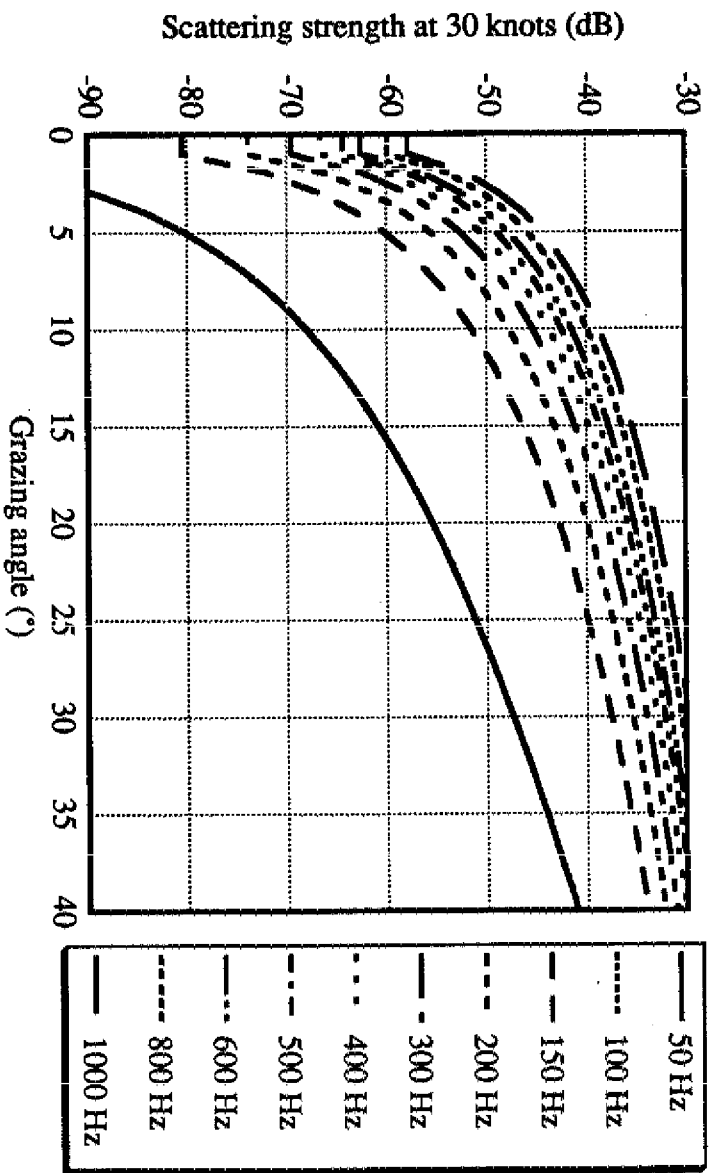300 Hz
400 Hz
500 Hz
600 Hz
800 Hz
1000 Hz

Fig. 8 — Surface scattering strengths as a function of grazing angle and frequency for a wind speed of 30 knots

4, the grazing angle is held constant at 10° and 30°, respectively, while wind speed and frequency vary. In Figs. 5 and 6, the frequency is held constant at 100 and 900 Hz, respectively, while in Figs. 7 and 8, the wind speed is held constant at 5 and 30 knots, respectively.

Comments about the behavior of the algorithm at some of the "edges" of the parameter space are in order. The effect of the 5-knot wind speed cutoff can be seen clearly in Figs. 3 and 4, while the 1° grazing angle cutoff is apparent in Figs. 5, 6, and 8. In Fig. 3, the transitions between perturbation theory and Chapman-Harris may seem too abrupt, but they in fact reflect the behavior of the data. The exceptions to this are the transitions at the lowest frequencies (not shown on Fig. 3) that occur above 30 knots. These transitions probably are too abrupt, but unfortunately there are no data on which to base a better prediction. The rolloff of the 50 Hz curves in Figs. 3 and 4 at low wind speeds may not be realistic in the presence of significant swell components, but again there are no data to support a better model. In any case, the rolloff probably gives a generally correct feeling for the importance of surface scatter in these conditions. In Fig. 7, the 50 Hz curve is off the bottom of the plot, and again this may be too low. The data on which the algorithm is based were analyzed with 70 Hz as the lowest frequency. While the 70 Hz levels from the algorithm generally give results in agreement with the data, the presence of swells may in fact keep the 50 Hz scattering levels in the deep ocean higher than a Pierson-Moskowitz surface spectrum would suggest. Again, there are no data on which to base a better prediction.

The algorithm itself has been written in two forms: as a FORTRAN function and as a Microsoft Excel® macro function. Figure 9 shows the FORTRAN code listings and Fig. 10 shows the Excel macro.

4. SUMMARY

An algorithm has been proposed for calculating surface backscattering strength for grazing angles between 0° and 40°, for wind speeds between 0 and 40 knots, and for frequencies between 50 and 1000 Hz. The algorithm is intended as a replacement for the Chapman-Harris empirical formula presently in use in virtually all low-frequency acoustic reverberation models.

The algorithm is based on data collected during the CST series of at-sea experiments. In each of the first five CST exercises, experiments were conducted to measure surface scattering strengths using broadband SUS charges as sources. The results of these experiments were compared to two existing methods for predicting surface scattering strengths: air-water interface scattering theory (in the form of first-order perturbation theory), and the Chapman-Harris empirical formula. Environmental conditions where either of the two predictive methods appear to be appropriate were identified, as well as a region that had levels that were intermediate between the two. The algorithm uses the CST data to identify where the boundaries of the scattering regions are and provides a smooth transition between the different calculation methods.

The algorithm described here should be regarded as an interim solution to the problem of predicting surface scattering strengths. On the one hand, the evidence is clear that the Chapman-

```
*=======================================================================
*
      REAL*4 FUNCTION  SURFACE_SS
     >        (wind_speed,frequency,grazing_angle)
*
*     This function calculates surface scattering strengths, given
*     wind speed in knots,
*     frequency in Hz,
*     grazing angle in degrees.
*
*     If the wind speed < 5.0 knots, the surface scattering strength
*     will be computed for a wind speed of 5.0 knots.
*     If the wind speed > 40.0 knots, the surface scattering strength
*     will be computed for a wind speed of 40.0 knots.
*
*     If the frequency is < 50.0 Hz or > 1000 Hz, an ERROR CONDITION
*     is returned.  The scattering strength will be set to +1000.
*
*     If the grazing angle is < 1.0, the surface scattering strength
*     will be computed for a grazing angle of 1.0 degrees.
*     If the grazing angle is > 40.0, the surface scattering strength
*     will be computed for a grazing angle of 40.0 degrees.
*
*
*=======================================================================


      real*4    beta
      real*4    chapman_harris_limit
      real*4    frequency
      real*4    grazing_angle,grazing_angle_r
      real*4    interpolation_factor
      real*4    perturbation_limit
      real*4    PI
      real*4    temp1,temp2,temp3,temp_ss
      real*4    wind,wind_speed

      parameter (PI = 3.1415927)


*---  if wind speed is out of range, reset it to the extremes:
      if (wind_speed .lt. 5.0) then
         wind = 5.0
      else if (wind_speed .gt. 40.0) then
         wind = 40.0
      else
         wind = wind_speed
      endif


*---  if frequency is out of range, return with an ERROR condition:
      if ((frequency .lt. 50.0) .or. (frequency .gt. 1000.0)) then
         surface_ss = 1000.0
         return
      endif


*---  if the grazing angle is out of range, reset it to the extremes
*---  also: convert to radians:
```

Fig. 9 – FORTRAN listing of surface scatter algorithm

```
      if (grazing_angle .lt. 1.0) then
         grazing_angle_r = PI/180.0
      else if (grazing_angle .gt. 40.0) then
         grazing_angle_r = 40.0 * PI/180.
      else
         grazing_angle_r = grazing_angle * PI/180.
      endif


*---  determine limit of perturbation theory range:
      if (frequency .ge. 240.0) then
         perturbation_limit = 14.0
      else
         perturbation_limit = 41.71 - 0.1155*frequency
      endif


*---  check if perturbation theory applies:
      if (wind .le. perturbation_limit) then
*---     use perturbation theory:
         temp1 = 1.43E7/(frequency**2.0)/(wind**4.0)
     >             / (cos(grazing_angle_r)**2)
*---     isotropic form of perturbation theory:
         temp2 = 1.61E-4 * tan(grazing_angle_r)**4.
     >            * exp(-min(temp1,200.0))
*---     perturbation theory scattering strength:
         if (temp2 .gt. 1.0E-20) then
            surface_ss = 10.*log10(temp2)
         else
            surface_ss = -200.0
         endif


      else
*---     find the chapman harris limit at this frequency:
         chapman_harris_limit = 39.07-0.066*frequency
     >           + 7.06E-5 * (frequency**2.) - 2.58E-8 * (frequency**3.)

*---     apply chapman harris formula:
         beta  = 158.*(wind*(frequency**0.3333))**(-0.58)
         temp1 = beta *3.3 * log10(grazing_angle/30.)
         temp2 = 42.4*log10(beta)
*---     chapman harris formula:
         temp3 = temp1 - temp2 + 2.6


*---     check if chapman harris formula applies directly:
         if (wind .ge. chapman_harris_limit) then
            surface_ss = max(temp3,-200.0)


         else
*---        find interpolation factor:
            interpolation_factor = (wind - perturbation_limit)
     >                    / (chapman_harris_limit-perturbation_limit)
            temp1 = 1.43E7 / (frequency**2.)/(wind**4.)
     >              / (cos(grazing_angle_r)**2.)
*---        isotropic form of perturbation theory:
            temp2 = 1.61E-4 * tan(grazing_angle_r)**4.
     >               * exp(-min(temp1,200.0))
*---        perturbation theory scattering strength:
            temp_ss = 10.*log10(temp2)
*---        interpolation done in dB space:
```

Fig. 9 — FORTRAN listing of surface scatter algorithm, continued

```
        temp_ss = temp_ss + interpolation_factor * (temp3-temp_ss)
        surface_ss = max(temp_ss,-200.0)
    endif
endif

return
end
```

Fig. 9 -- FORTRAN listing of surface scatter algorithm, continued

Surface_SS	Surface scatter algorithm based on CST SUS
=ARGUMENT("wind")	wind speed in kts
=ARGUMENT("freq")	frequency in Hz
=ARGUMENT("angle")	grazing angle in degrees
=IF(OR(freq<50,freq>1000),RETURN(1000))	test for in-range values
=IF(angle<=1,1,angle)	lower angle limit of 1 deg
=IF(A60>40,40,A60)	upper angle limit of 40 deg
=IF(wind>40,40,wind)	upper wind limit of 40 kts
=IF(A62<=5,5,A62)	lower wind limit of 5 kts
=IF(freq>=240,14,41.71-0.1155*freq)	determine limit of pert. theory range
=IF(A63<=A64,GOTO(A78))	branch if pert. theory applies
=39.07-0.066*freq+0.0000706*freq^2-0.0000000258*freq^3	CH limit at this frequency
=IF(A63>=A66,GOTO(A82))	branch if CH applies
=(A63-A64)/(A66-A64)	interpolation factor
=158*(A63*freq^(1/3))^(-0.58)	beta
=3.3*A69*LOG10(A61/30)	
=42.4*LOG10(A69)	
=A70-A71+2.6	Chapman-Harris formula
=14300000/freq^2/A63^4/COS(A61*PI()/180)^2	exponential of PM - note conversion to kts
=0.000161*TAN(A61*PI()/180)^4*EXP(-MIN(A73,200))	isotropic form of pert. theory
=10*LOG10(A74)	pert. theory SS
=A75+A68*(A72-A75)	interpolation done in dB space
=RETURN(MAX(A76,-200))	return interpolated SS
=14300000/freq^2/A63^4/COS(A61*PI()/180)^2	exponential of PM - note conversion to kts
=0.000161*TAN(A61*PI()/180)^4*EXP(-MIN(A78,200))	isotropic form of pert. theory
=10*LOG10(A79)	pert. theory SS
=RETURN(MAX(A80,-200))	return perturbation theory SS
=158*(A63*freq^(1/3))^(-0.58)	beta
=3.3*A82*LOG10(A61/30)	
=42.4*LOG10(A82)	
=A83-A84+2.6	Chapman-Harris formula
=RETURN(MAX(A85,-200))	return CH SS

Fig. 10 -- Excel spreadsheet macro listing of surface scatter algorithm

Harris formula does a poor job of predicting surface scattering strengths for many combinations of surface conditions and frequencies, though there are certainly regimes where it appears to do a good job. For those regimes where Chapman-Harris is inadequate, even a simple perturbation theory calculation such as that contained in this algorithm does a better job of predicting scattering strengths. The existence of a transition region between air-water interface scattering and (presumably) scattering from subsurface bubbles is also a reasonable thing to expect; while the boundaries we have drawn are only approximations, there is considerable evidence to show that they are approximately correct.

On the other hand, the surface scattering problem is clearly more complex than this algorithm suggests. The principal objection to the algorithm is that it is unlikely that surface scattering strengths can be predicted accurately on the basis of a single environmental parameter, and that even if it could, that parameter would probably not be instantaneous wind speed measured at any height. It will be necessary in future work to identify how factors such as wind stress, wind history, sea state, and water temperature affect surface scattering so that a more complete model can be constructed.

5. ACKNOWLEDGMENTS

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